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PRELIMINARY DESIGN OF AN ANALOG DISCRETE UNIFORM NOISE GENERATOR
IDEJNI PROJEKAT GENERATORA ANALOGNOG DISKRETNOG UNIFORMNOG ŠUMA

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ABSTRACT

The paper presents the basic idea of the construction and a practical realization of a novel analog discrete uniform noise generator. The source of noise is a carbon resistor, the noise signal is linearly amplified and its value is limited in the finite small range [- xg, xg]. The probability density function (PDF) of the carbon resistor thermal noise in that region is square one. By narrowing the symmetric allowable gap (interval) around zero, PDF of the noise approaches a uniform distribution. The factor of deviation from the uniform distribution is precisely defined and its value is practically negligible. In addition, the paper discusses the application of the proposed dither noise, both in the two-bit and in the multi-bit stochastic digital measurement method (SDMM). It is shown that noise is more suitable for application in multi-bit SDMM, because it is less sensitive to deviations from the uniform distribution.

Keywords: *analog discrete uniform noise generator, two-bit SDMM, multi-bit SDMM, D/A conversion.*

REZIME

U radu je predložen potpuno novi i originalni princip generisanja analognog diskretnog uniformnog šuma. On, bar za red veličine, proširuje propusni opseg instrumenta u kojem se primenjuje i njegovi odmerci su analogni, dakle, neograničeno visoke rezolucije. U radu je data principijelna šema generatora šuma koja pokazuje kako se može, kao primarni izvor šuma, primeniti ugljeni otpornik. Pored toga, u radu su objašnjene i granice u kojima je šum generisan. Pokazano je da one zavise od dozvoljenog stepena izobličenja, primenjenog linearnog pojačanja i standardne devijacije šuma u otporniku. U dodatku rada je dato strogo izvođenje nekoliko relacija: relacije koja opisuje kvadratnu zavisnost funkcije gustine raspodele verovatnoće u okolini nulte vrednosti šuma, relacije koja opisuje srednju vrednost funkcije gustine raspodele šuma, i relacije koja opisuje granice funkcije gustine raspodele verovatnoće i njihov odnos prema srednjoj vrednosti šuma. U dodatku je, takođe, prikazana i preciznija majorantna definicija faktora izobličenja uniforme raspodele. Stohastička digitalna merna metoda je dosad najtačnija merna metoda za merenja energije, a generator diskretnog digitalnog šuma, u najtačnijoj standardnoj varijanti metode, je i najskuplji deo instrumenta. To je, uz proširenje frekventnog opsega, bio glavni motiv za formulisanje alternativnog i potencijalno naprednijeg rešenja.

Ključne reči: *Generator analognog diskretnog uniformnog šuma, stohastička digitalna merna metoda, digitalno-analogna konverzija.*

INTRODUCTION

The motivation for writing this paper is the need for a quality analog discrete uniform noise generator (ADUNG) that would find application in stochastic digital measurements (SDMs) *(Vujicic V. et. al., 1999), (Vujicic V. et. al., 2009), (Vujicic V. et. al., 2014), (Radonjic. et. al., 2012), (Sovilj P. et. al., 2016), (Urekar M. et. al., 2017)*. In *(Sovilj P. et. al., 2019)* a strict definition of simple analog-to-digital (A/D) conversion and simple signal processing within a simple SDM method (SDMM) is given. Both mentioned processes are either one-bit or two-bit. This fact implies simple hardware and only a few sources of systematic error that can be easily identified and eliminated *(Urekar M. et. al., 2017), (Vujicic V. et. al., 2020)*. The final result is an exceptional accuracy of a simple SDMM.

Increasing the SDMM resolution, of course, leads to better accuracy. In *(Urekar M., 2018)*, for example, it was shown that increasing the resolution by one bit is equivalent to the application of approximately four times faster technology. However, the price for this is twice as complex hardware, and thus twice as many sources of systematic error. For these reasons, the author of *(Urekar M., 2018)* concluded that the optimal SDMM resolution is three bits. In that case, the effective processing speed is nine times higher compared to a two-bit SDMM.

Despite this, there are many instruments that are based on a simple SDMM *(Vujicic V. et. al., 2019)*. The common feature of all of them is a high accuracy, as well as the possibility of parallel measurement and parallel signal processing. Some instruments, for example, can detect the basic and most significant higher harmonics in a power grid (PG), while others can reduce a large amount of data in a PG.

An indispensable part of all these instruments is the ADUNG (Fig 1.) The reason is that SDMM is a digital measurement of the mean product of two signals in a time interval, where the noise signals are added to the input signals before the A/D conversion. The two noise signals must be uncorrelated, evenly distributed, have the mean value equal to zero and be limited to within one half of the A/D converter quantum.

MATERIAL AND METHOD

Thermal noise of a resistor has a Gaussian distribution probability *(Haus H., 2000)*:

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2} . \qquad (1)$$

Now, assume that the noise x can be linearly amplified k times in the range of interest (at least in 3σ). In that case, we can write:

$$f(kx) = \frac{1}{k \cdot \sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{kx}{k\sigma}\right)^2} \quad (2)$$

In $x \leq xg \approx 0$ (Fig. 2) region $x = 0$, $kx = 0$ is the deviation factor of the Gaussian distribution from the uniform one:

$$Q = \frac{1}{2} \cdot \frac{f(k \cdot 0) - f(k \cdot x_g)}{f(k \cdot 0)} \approx \frac{1}{4} \cdot \frac{x_g^2}{\sigma^2} \quad (3)$$

Table 1 shows the characteristic values of x_g and kx_g depending on the deviation factor Q (note: $k = 10^5$ and $\sigma = 10^{-6}V$). A detailed derivation of equation (3) is given in the Appendix.

Table 1. Four characteristic values of x_g and kx_g.

Q	x_g [V]	kx_g [V]
10^{-3}	$6.32 \cdot 10^{-8}$	$6.32 \cdot 10^{-3}$
10^{-4}	$2 \cdot 10^{-8}$	$2 \cdot 10^{-3}$
10^{-5}	$6.32 \cdot 10^{-9}$	$6.32 \cdot 10^{-4}$
10^{-6}	$2 \cdot 10^{-9}$	$2 \cdot 10^{-4}$

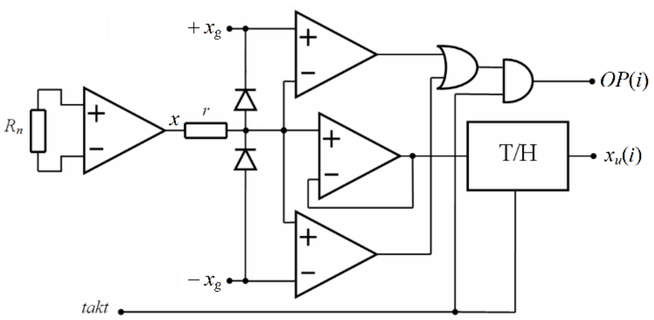
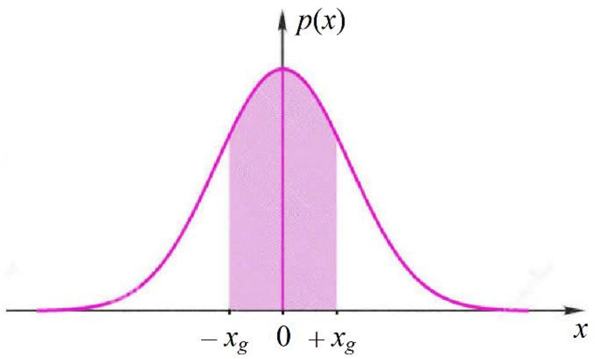
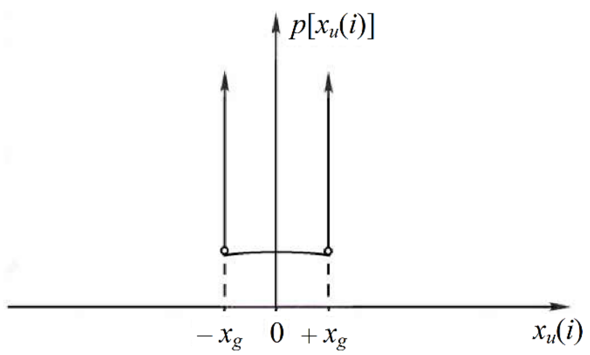


Fig 1. The block diagram of the ADUNG.



a)



b)

Fig 2. a) The probability density function of the thermal noise in the resistor and b) the probability density function at the output of the T/H circuit.

Theory and previous experience *(Vujicic V. et. al., 2019), (Vujicic V. et. al., 2020)* have shown that the ADUNG must have the following characteristics:

1) it must generate a voltage signal of truly uniform distribution,

2) its samples must be uncorrelated with each other (autocorrelation output function of the ADUNG must be equal to zero),

3) its samples must be within the range of one quantum of a stochastic A/D additive converter,

4) its samples must be evenly distributed at time intervals,

5) its samples must be analog (i.e. they must have an infinitely high resolution).

Only such ADUNG can replace the existing solution based on the random number generator and the D/A converter and, eventually, overcome its limitations. In the existing solution, the bottleneck is the D/A converter, i.e. its bandwidth *(Clara M., 2013)*.

Analog discrete random samples at the output of the ADUNG are divided into two classes: 1) non-uniform random samples when the output binary signal OP(i) has a value 0 and 2) uniform random samples, when the output binary signal has a value of 1. For the purpose of digital measurement and digital signal processing only samples from the second class are used.

The thermal noise in the resistor, which is used as a source, has a normal (Gaussian) probability density function with a mean value of zero. Within sufficiently narrow limits around zero (|x| < |xg|) the Gaussian distribution is uniform (Fig. 2). The thermal noise from the resistor is amplified by a linear voltage amplifier and then fed to the symmetrical double-sided diode limiter via a series resistor.

When the value of the amplified thermal noise is within the limits |x| < |xg|, the diodes are blocked due to the reverse voltage and the output binary signal has a value of 1. At these instants, the current value of the amplified thermal noise is processed. On the other hand, when the value of the amplified thermal noise is outside the above limits, the output binary signal has a value of 0 and the current value of amplified thermal noise is not processed.

An important element in this idea is the track and hold (T/H) circuit. If the gap between symmetrical limits of the diode limiter are narrow (|xg| → 0), the T/H circuit can operate at a very high frequency and thus overcome the problem of the narrow bandwidth of the ADUNG.

RESULTS AND DISCUSSION

The closer the value of |xg| is to zero, the distribution from Fig. 3 is closer to the uniform area. This idea can be used to design the ADUNG, but care must also be taken of how the T/H circuit will be designed. For example, if the value of |xg| is small compared to the voltage range of the T/H circuit, its frequency range can be increased by two to three orders of magnitude. In that case, even rare events, such as probability p (|x| < |xg|), can have an acceptable frequency. The preliminary analyses show that the frequency of such an event can go, with available T/H circuit technology, up to 20 MHz. A comprehensive analysis of this problem goes beyond the scope of this paper. The proposal, presented in the paper, is intended for the scientific and professional public in the field of measurement and metrology because it raises the frequency range of SDMM by more than an order of magnitude and practically provides analog (infinitely large) resolution of the dither signal.

The ADUNG can be applied in both two-bit and multi-bit SDMM. Each of these applications has certain advantages:

1) the two-bit SDMM has a simple calculation of polynomials coefficients and, therefore, application in measurements with nonlinear sensors *(Sovilj P. et. al., 2020)*, and

2) the multi-bit SDMM allows the application of wider limits around the zero value of noise and is less sensitive to the value of the degree of non-uniformity Q.

Table 1 shows typical values of amplification and standard deviations of thermal noise. For Q = 10-3, the quantum of multi-bit flash A/D converter is about 12mV *(Clara M., 2013)*. Then, the ten-bit flash A/D converter (which has 511 positive and 511 negative quantum levels plus the zero quantum level) can have a range from -6.5 V to +6.5 V, and with the application of crosswitching technique at least 20-bit expected accuracy in a sufficiently long time interval. At the moment, the multi-bit SDMM seems more favorable from the point of view of the application of the ADUNG. On the other hand, modern electricity meters use current sensors in the range from -0.3 V to +0.3 V, which, with a nine-bit flash AD converter, cross-switching technique and Q = 10-4 gives the expected accuracy of at least 22 bits.

CONCLUSION

The paper presented the concept of a novel analog discrete uniform noise generator. The circuit diagram of this device is given and the principle of its operation is described. Then, the main advantages of the proposed device are listed, and they are infinitely large resolution and at least an order of magnitude higher frequency bandwidth. However, it should be emphasized that it is necessary to make a great engineering effort to make a physical device that would be at the level of existing ones, especially in terms of accuracy.

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APPENDIX

1. Analytical expression of the function f(kx) in the vicinity of zero.

$$f(kx)=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot e^{-\frac{1}{2}\left(\frac{kx}{k\sigma}\right)^2}=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2}$$

Since

$$e^{-t}=1-\frac{t}{1!}+\frac{t^2}{2!}-\cdots+(-1)^n\cdot\frac{t^n}{n!}$$

it follows

$$f(kx)=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left[1-\frac{x^2}{2\sigma^2}+\frac{1}{2!}\cdot\left(\frac{x^2}{2\sigma^2}\right)^2-\cdots\right.$$

$$\left.+(-1)^n\cdot\frac{1}{n!}\cdot\left(\frac{x^2}{2\sigma^2}\right)^n\right].$$

If -xg < x < xg, or |x| < |xg| and |xg| → 0, the previous expression reduces to

$$f(kx)\approx\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left(1-\frac{x^2}{2\sigma^2}\right).$$

2. The mean value of the function f(kx) in the vicinity of zero.

$$\overline{f(kx)}\approx\frac{1}{2\cdot x_g}\cdot\frac{2}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot$$

$$\int_0^{x_g}\left(1-\frac{x^2}{2\sigma^2}\right)dx=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left(1-\frac{x_g^2}{6\sigma^2}\right).$$

3. Boundary limit values of the function f(kx).

a) $f(k\cdot 0)=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}$

b) $f(k\cdot|x_g|)=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left(1-\frac{x_g^2}{2\sigma^2}\right)$

4. Deviation of the limit values of the function f(kx) from the mean value.

a) $f(k\cdot 0)-\overline{f(kx)}=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}-$

$-\left[\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left(1-\frac{x_g^2}{6\sigma^2}\right)\right]=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\frac{x_g^2}{6\sigma^2}$

b) $f(k\cdot|x_g|)-\overline{f(kx)}=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot$

$\left(1-\frac{x_g^2}{2\sigma^2}-1+\frac{x_g^2}{6\sigma^2}\right)=\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left(-\frac{1}{3}\cdot\frac{x_g^2}{\sigma^2}\right)\cdot$

It can be seen that the values of f(kx) at the boundaries are twice as far from the mean value $\overline{f(kx)}$ as $f(k\cdot 0)$. Therefore, the majorant value of the factor of deviation of the Gaussian distribution from the uniform one near zero is somewhat higher and amounts to

$$Q_k=\frac{\overline{f(k\cdot x)}-f(k\cdot|x_g|)}{\overline{f(k\cdot x)}}$$

$$=\frac{\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left(-\frac{1}{3}\cdot\frac{x_g^2}{\sigma^2}\right)}{\frac{1}{k\cdot\sigma\cdot\sqrt{2\pi}}\cdot\left(1-\frac{1}{6}\cdot\frac{x_g^2}{\sigma^2}\right)},$$

$$=-\frac{1}{3}\cdot\frac{x_g^2}{\sigma^2}\cdot\left(1+\frac{1}{6}\cdot\frac{x_g^2}{\sigma^2}\right)\approx-\frac{1}{3}\cdot\frac{x_g^2}{\sigma^2}$$

$$\frac{|Q_k|}{|Q|}=\frac{1/3}{1/4}=\frac{4}{3}=1.333$$

We see that $|Q_k|$ and $|Q|$ are of exactly the same order of magnitude, i.e. that $|Q_k|$ is only 33% larger than $|Q|$. Since these are very small values (quantities), such a difference is negligible.

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